EFFECTS OF NEUROMUSCULAR TENSION IN THE USE OF AN ISOMETRIC HAND CONTROLLER

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THESIS

EFFECTS OF NEUROMUSCULAR TENSION IN THE USE OF AN ISOMETRIC HAND CONTROLLER

by

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December 1972

Effects of Neuromuscular Tension in the
Use of an Isometric Hand Controller

by

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ABSTRACT

The effects of operator workload on average grip pressure and of neuromuscular tension on tracking performance were the objects of this research. In one experiment, a "sub-critical" tracking task was performed by the operator while measurements of grip pressure were taken. In a second experiment, the operator was required to maintain average grip pressure at specified levels during 100-second tracking tasks while his RMS tracking error was measured. The results clearly indicate that average grip pressure increases as the workload increases and that higher average grip pressures result in higher RMS tracking error values.

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TABLE OF SYMBOLS

λ	Instability factor
λ_c	Critical instability factor
P_g	Instantaneous grip pressure
$\bar{P}_g$	Average grip pressure
P_m	Averaged maximum grip pressure
s	Laplace transform operator
K	Gain
$i(t)$	Instantaneous forcing function

ACKNOWLEDGEMENT

The author wishes to acknowledge Assistant Professors M. H. Redlin and R. A. Hess for their many helpful suggestions. Appreciation must also be expressed to the subjects who made it all possible. Last, but not least, a thank you to my wife whose patience knew no limit.

1. INTRODUCTION

There are two significant problems in the design of military aircraft, both of which have received increased amounts of attention in recent times. These problems are: weight reduction (the F-111 was to heavy for Navy use) and aircraft survivability (the conflict in S.E. Asia serves as a reminder).

One system which offers a significant advance in the solution of these two problems is the fly-by-wire control system in which the control inputs from the pilot are processed electronically. With the use of microelectronics, fly-by-wire control systems can be much lighter than the mechanical and/or hydraulic systems now in use. With the need for hydraulic lines greatly reduced, or eliminated, control circuits can easily be duplicated or even triplicated. The result would be a significant increase in aircraft survivability with essentially zero weight penalty. These systems also allow considerable flexibility in the choice of cockpit controls [Ref. 1].

Although not specifically considered in Ref. 1, isometric controllers (rigid controllers whose electrical outputs are proportional to applied force) have significant advantages. Among these are lightness, simplicity, reliability, ruggedness and linearity. In addition, the superiority in tracking experiments of isometric controllers over more conventional displacement controllers

(moveable controllers whose electrical outputs are proportional to deflection), has been demonstrated on many occasions [Refs. 2, 3, 4, and 5]. When the isometric controller was compared to a conventional displacement controller in a simple pursuit tracking task it was reported that [Ref. 5]:

> "...it appears that pressure control has definite superiority, even in simple control tasks, and that the margin of superiority increases as a function of task difficulty."

Flight tests with the isometric controller have been disappointing [Refs. 6, 7, and 8]. The disappointments seem to come, primarily, from lack of a good understanding of the isometric controller. As an example, although Russell and Alford [Ref. 6] indicated that the addition of stick friction would have improved the performance of the isometric stick, another major improvement could have been accomplished by shortening the controller and mounting it in a side-arm configuration. This would have reduced the inertia effects caused by the pilot's arm and shoulder.

However, the virtues of isometric control devices will eventually dictate their usage in cockpits of the future. Therefore a closer examination of the isometric controller as the major element of a control system is required. Specifically, in the opinion of many Professors and students at the Naval Postgraduate School the effect of

neuromuscular tension as evidenced by the pilot's grip pressure may be a significant interface parameter with regard to overall system performance.

In conducting tracking experiments involving unstable controlled elements, it was noted that the more difficult tasks (those involving the higher levels of instability) induced increased grip pressure on the part of the operator [Ref. 9]. Although these results were qualitative and based only on the experimenters observations and operator comments, it appeared that increased operator workload caused increased average grip pressure. (Here, "workload" refers to that fraction of the operators maximum control capacity being utilized in the task at hand.) This hypothesis has been further confirmed by discussions in which carrier qualified pilots at the Naval Postgraduate School indicated that flight situations involving a good deal of "psychological stress" induce a "white knuckle" grip on the aircraft control stick. The term "psychological stress" refers to a situation where the pilots survival is considered by him to be in jeopardy; e.g. a night carrier landing in bad weather with low fuel state.

A survey of the literature involving laboratory tracking experiments using isometric manipulators indicated that the effects of neuromuscular tension on tracking performance have been essentially neglected. However, the effect of muscular tension on the operation of aircraft rudder pedals has been considered [Ref. 10]. The results indicated

a significant increase in the operator's time delay with increased muscle tension but the experiment was not extended to include hand controllers. Additionally in another research effort, average grip pressure was recorded in the operation of an isometric fingertip controller [Ref. 11]. Although the pressure measurements were biased by control activity the authors stated that grip pressure measurements could be used to measure systemic muscle activity and that average grip pressure was a good indicator of muscular tension during tracking.

At this point, a more detailed discussion of the human controller interface is in order. Shown in Fig. 1 is a block diagram intended as a functional rather than a structural analog of the human. Particularly important is the block denoted G_k. This represents proprioceptive feedback cues [Ref. 12]. These cues provide information as to the degree of contraction of muscles and the state of tension in the tendons [Ref. 13]. The block has a secondary input denoted "neuromuscular tension." This diagram represents one possible functional explanation of the effect of neuromuscular tension in the operation of an isometric device, i.e., a change in the form or quality of proprioceptive feedback.

The quality of this feedback is very important in the performance of any control device. It has been suggested that the superiority of isometric control sticks in positioning type control systems is due to the greater accuracy

of force (as opposed to displacement) proprioceptive feedback [Ref. 14]. Thus, the quality of the force proprioceptive feedback must be considered as an important parameter effecting overall performance and acceptability of the isometric controller.

It has already been indicated that increased workload and/or "psychological stress" may induce increased grip pressure. The increased grip pressure would manifest itself in increased neuromuscular tension in the hand, wrist, forearm and to a lesser extent in the upper arm. It is expected that this increased muscular tension, not directly related to the operator's control inputs, will modify the proprioceptive feedback in some way. If this happens tracking performance using the isometric stick will be altered. It is anticipated that the uncorrelated muscle tension will act as a preload on the open loop neuromuscular control system. This decreases the sensitivity to the small variations in muscle tension necessary for small, precise corrections, thereby degrading tracking performance.

The implications of such a sequence of effects as outlined above are both obvious and ominous. In a critical situation, under stress, a pilot could easily over-control his aircraft. Such an event might well be fatal.

If the effects of grip pressure on tracking performance can be quantified, then appropriate measures can be found to reduce or eliminate those effects. It was to the problem of identification and quantification that this thesis was directed.

The following proposed cause-effect relationship was investigated:

workload psychological stress	neuromuscular tension	performance

The hypothesis was that workload and/or psychological stress causes an increase in neuromuscular tension which in turn degrades performance in a compensatory tracking task. Since the kind of psychological stress defined here was difficult to create artifically, increasing operator workload was used to simulate it. The research was conducted in two phases:

<u>Phase I</u>: Experiments designed to determine and quantify the effects of operator workload on average grip pressure while using an isometric hand controller.

<u>Phase II</u>: Investigate the effects of grip pressure on performance as measured by tracking proficiency using an isometric hand controller in a continuous, stable tracking task.

II. EXPERIMENTAL PROCEDURE

A. PHASE I

In order to determine the effects of operator workload on average grip pressure it was necessary to fabricate a control stick from which grip pressure and control measurements could be obtained simultaneously. Also of importance was the elimination of the bias effects reported in Ref. 4. This was done by mounting a plexiglass cylinder on top of a set of aluminum flexures as shown in Fig. 2. The strain gages in the grip area provided the pressure output and those on the flexures the control outputs. Bridge circuits as shown in Fig. 3 were used to apply the strain gage signals to an EAI Model 580 analog computer.

In order to reduce temperature effects rosettes were used for compensation in the grip area. The active rosette elements used for grip pressure measurement had their major axes aligned circumferentially. The elements rotated 90° from those used for grip pressure were used in adjacent legs of the bridges as temperature compensators.

To remove the effect of control force from the pressure sensing bridges a sufficient amount of the control signal was subtracted from the pressure sensing output to cause the pressure output to read zero under the application of a point applied load. This subtraction was done using operational amplifiers contained, along with the bridge circuits, in the box shown in Fig. 4. In addition, the

difference in moment arm between the flexures was compensated for by decreasing the gain of the bridge amplifier being driven by the lower flexure. The signals from the controller to the analog computer consisted of grip pressure unbiased by control movements and control signals proportional to the force applied to the controller.

In the first experiment, the first order critical task [Ref. 13] was implemented on the analog computer. The task was set up as a two-axis tracking problem. This allowed the determination of the effect that the two-axis task would have on the values of λ_c as reported in Ref. 11. The display consisted of a tracking dot presented on a CRT. The value of λ_c was recorded when the dot first reached the edge of a four inch square centered on the CRT face. This square was referred to as the tracking window. When the tracking dot reached the edge of the tracking window the problem automatically terminated. Over-all system gain was established so that a control force of five pounds was required in order to move the tracking dot from the center of the presentation to the edge of the tracking window. The low signal-to-noise ratio of the grip pressure signal required the use of two low pass filters, as shown in the circuit diagram (Fig. 5).

Information concerning flight time and gross physical characteristics of the four naval aviators used as subjects, is shown in Table I. The subjects were well trained, having completed a minimum of 300 runs on the first order critical

task, prior to the beginning of the experiment. A typical learning curve is shown in Fig. 6. Once training was completed the subjects were told that data was now being taken but otherwise the first experiment was performed exactly as the training periods had been. For the first set of data, grip pressure and λ_c were recorded. Typical results are shown in Fig. 7.

In order to confirm and quantify the tendency for increasing λ to cause an increase in grip pressure a second experiment, involving a sub-critical task, was performed. In this experiment $\dot{\lambda}$ was set equal to zero and the trials were run as before with one other exception. The trials were limited to 25 seconds duration and λ was varied in discreet amounts between succeeding runs. The results were plotted showing $\frac{\lambda}{\lambda_c}$ vs. $\frac{P_g}{P_m}$; examples of which are shown in Figs. 8, 9, 10 and 11. The value of λ_c used for each subject was obtained by averaging the values of λ_c attained over the last 50 runs of the previous experiment. To obtain the normalizing factor for grip pressure each subject was asked to maintain as tight a grip as possible for 5 seconds. The average maximum over 5 trials was taken as a maximum pressure (P_m) for that subject and used as the normalizing factor.

B. PHASE II

In Phase II the objective was to determine what effect, if any, an increase in average grip pressure would have on tracking performances. The tracking task selected is shown

schematically in Fig. 12. The analog circuit diagram is shown in Fig. 13. In order to maintain different levels of average grip pressure, it was necessary to impose a secondary task on the operator. Two lights were presented to the operator in the configuration shown in Fig. 14. The light to the left of the operator came on if the operator's grip pressure dropped below a specified preset value. The light on the operator's right came on if the grip pressure exceeded a specified value. The average maximum grip pressure determined previously was used as a basis for setting the grip pressures required.

In order to determine how many different levels of pressure the subjects could be asked to use, it was necessary to determine the maximum amount of pressure the subjects could maintain for 100 seconds without fatigue becoming the major factor. In addition, the tolerances to which the pressure had to be maintained had to be determined.

Tracking runs, by a volunteer not in the data base, were made at several different pressure levels and a value of 0.6 P_m was decided upon as the maximum level to be required. It was felt that the value 0.6 P_m was an acceptable compromise between the desire to have the operator maintain a high grip pressure and the necessary considerations of fatigue. It is well recognized that high stress situations such as that being simulated are unlikely to exist in real life for a continuous period of 100 seconds as the tracking runs did.

Further tests were made with the volunteer mentioned above to determine an "optimum" tolerance on the desired pressure level. With minimum distraction from the primary task as the deciding factor, the subjective opinion of the volunteer was that a value of ±3 psi should be used. Because of the tolerances imposed, the maximum pressure to be required, and the necessity for having each pressure level distinct from the next, it was necessary to pair the subjects into two groups. Subjects JT and LK comprised a group which had high enough values of P_m to allow three pressure levels. Subjects JA and RK were only asked to perform at two pressure levels because their values of P_m were too low to allow three levels without overlap.

In order to remove any learning effects from the results, each subject was given a sufficient number of trials, without requiring a specific grip pressure, to enable his RMS tracking error to stabilize. Subjects LK and JT were then asked to maintain an average grip pressure equal to 0.2 P_m while accomplishing the tracking task. Again sufficient runs were made to allow the RMS error to stabilize, thereby accounting for the effects of the secondary task. With the value of RMS error at an average grip pressure of 0.2 P_m as a basis for comparison, tracking runs were then conducted at average pressures of 0.4 P_m and 0.6 P_m. No more than two runs were made at either of these values because fatigue became a major factor beyond that point. Subjects JA and RK

were asked to maintain an average grip pressure equal to $0.4\ P_m$ for a sufficient number of runs to allow the RMS error to stabilize. Then one run each was made at an average grip pressure equal to $0.6\ P_m$.

III. PRESENTATION OF RESULTS

The results obtained confirm the hypothesis that increased workload causes increased muscle tension, which then causes a decrease in tracking proficiency.

A sample result from the first experiment of Phase I is shown in Fig. 7. The traces clearly indicate that as the level of instability increased the grip pressure also increased. This tendency was not altered as the task was practiced. The peak in the grip pressure which occurs just after the value of λ_c is attributed to a final almost convulsive effort on the part of the subjects to recover the task in that brief instant between the time they realized that they'd lost control and the time the problem actually self-terminated. Subject RK's trace shows almost no pressure change throughout the runs. This was due to the fact that he tended to grasp the stick at the tip, which did not generate enough signal to be detected reliably. However, in later experiments it was seen that he exhibited characteristics quite similar to those of the other subjects.

The results from the second experiment in Phase I are shown in Figs. 8, 9, 10, and 11. The curves should be analyzed in two parts. For values of $\frac{\lambda}{\lambda_c}$ up to about 0.5 the task is apparently putting no appreciable stress or workload on the operator that can be evidenced by increased grip pressure. This is evidenced by the scattering of the data up to that point. From values of $\frac{\lambda}{\lambda_c} \geq 0.5$ all subjects

show a definite tendency to increase their grip pressure as the workload increases. It would be interesting to investigate exactly why $\frac{\lambda}{\lambda_c} = 0.5$ seems to be a point at which the operator begins to feel pressed by the system.

In the results of Phase II we can clearly see the degrading effect that an increased average grip pressure had on tracking performance. The curves shown in Figs. 15, 16, 17, and 18 are presented in three parts. The first is essentially a learning curve. The second consists of the learning curve for the tracking task when combined with the secondary task. The data here are from the lowest average grip pressure the particular subject was asked to maintain. The third shows the effect of increasing the average grip pressure. It is clearly shown that an increase in average grip pressure caused a corresponding increase in the RMS tracking error. Some actual grip pressure recordings taken during this experiment are presented in Fig. 19. It can be seen that the subject was able to maintain an average grip pressure close to that requested without a great deal of searching. In some cases the limits imposed by the lights were exceeded no more than once or twice during the entire 100-second run. This indicated that the secondary task was not a particularly distracting one and therefore its inclusion should not appreciably affect the phenomenon under investigation.

IV. CONCLUSIONS

Basically there are two conclusions to be drawn from this research:

1. Increased operator workload causes an increase in muscular tension which is manifested by an increase in average grip pressure.
2. Increased average grip pressure is a definite degrading factor in a subject's ability to perform a tracking task using an isometric control.

In addition to the two main conclusions it has been shown that the "critical task" tracking problem of Ref. 13 is an effective research tool in the study of manual control systems. The "critical task" can be used in workload studies and the parameter $\frac{\lambda}{\lambda_c}$ seems to be closely related to the percentage of total capacity at which an operator is actually performing. The "critical task" was shown to be an effective simulator of psychological stress (of a certain type) and could be used to investigate other changes in performance that tend to occur during periods of stress, such as target fixation, scan breakdown and failure to notice small but sometimes critical changes in aircraft instrument readings.

An important by-product of this research is the proposed use of average grip pressure as a direct indicator of workload, particularly at high workload levels. The ratio $\frac{P_g}{P_m}$ can be related directly to $\frac{\lambda}{\lambda_c}$ (per cent of maximum

workload) above values of $\frac{\lambda}{\lambda_c} = 0.5$. Thus an indication of percentage of workload, in any task in which a control stick is used, can be obtained from average grip pressure measurements, provided that the workload be approximately 50% of the operators maximum capacity or higher.

V. RECOMMENDATIONS

Both as a result of the experimental data obtained and from subject comments during this research, it is clear that many problems with isometric controllers still remain to be examined. It is firmly believed that isometric controllers offer such overwhelming advantages to the aircraft designer that they cannot be cast aside and, if this future role is to become a reality, much more research is needed. Some of the problems are discussed below:

Problem One: The subjects in this research commented frequently on the ease with which fore and aft control inputs could be made compared to the difficulty in producing sideways or lateral inputs. The reason for this is obvious if one tries grasping a rigidly mounted cylinder and pulling it to him and then compares that with trying to move the cylinder to the right or left.

Recommendation: This reaction needs to be quantified to determine how much difference there is in control power between the two channels and how the difference varies between individuals. It might be discovered that a simple change of gain in one channel would cure the problem.

Problem Two: All the subjects reported a difficulty with putting in a control signal in one axis only. Even those subjects who had previously used a control stick rather than a yoke felt it was more difficult to keep the lateral and longitudinal inputs separate, with the isometric controller.

Recommendation: Again the effect, if indeed it actually exists, needs to be quantified. One area of investigation should be to determine how much lateral control signal is generated in a single-axis (longitudinal) tracking task. It could be that a form of non-linearity about the neutral point could cure the problem.

Problem Three: A better method of measuring grip pressure needs to be devised. Although the prototype controller used in this research yielded satisfactory results, electrical noise, temperature and hysteresis effects in the plexiglass and the low signal levels inherent in the use of strain gages on plexiglass were problems.

Recommendation: A controller with a hydraulic or pneumatic bladder in the grip area might be a better pressure transducer. The controller design problem is primarily one of being able to isolate the control force effects from the grip pressure measurements.

Problem Four: The results reported here are based on a minimal amount of data. To be certain of the universal validity of these findings, more subjects need to be tested over more trials, particularly with regard to grip pressure effects on tracking performance.

Recommendations: In choosing more subjects, care should be taken to include some non-pilot, non-aviation oriented people. It may well be that characteristics exhibited by trained aviators may not be found in a random sample of the population.

One further recommendation, not problem oriented, concerns further evaluation of the idea of using average grip pressure as an indicator of workload. It is strongly recommended that many more experiments, such as the second experiment in Phase One of this research, be conducted. It may be possible to determine a universally applicable empirical relationship between workload and grip pressure. If expanded research upholds the findings reported here then experimenters will have in hand a valuable tool for measuring not only workloads in primary tasks but the effects of secondary tasks on overall operator workload as well. Such a finding would be a significant contribution to the entire field of manual control studies.

TABLE I

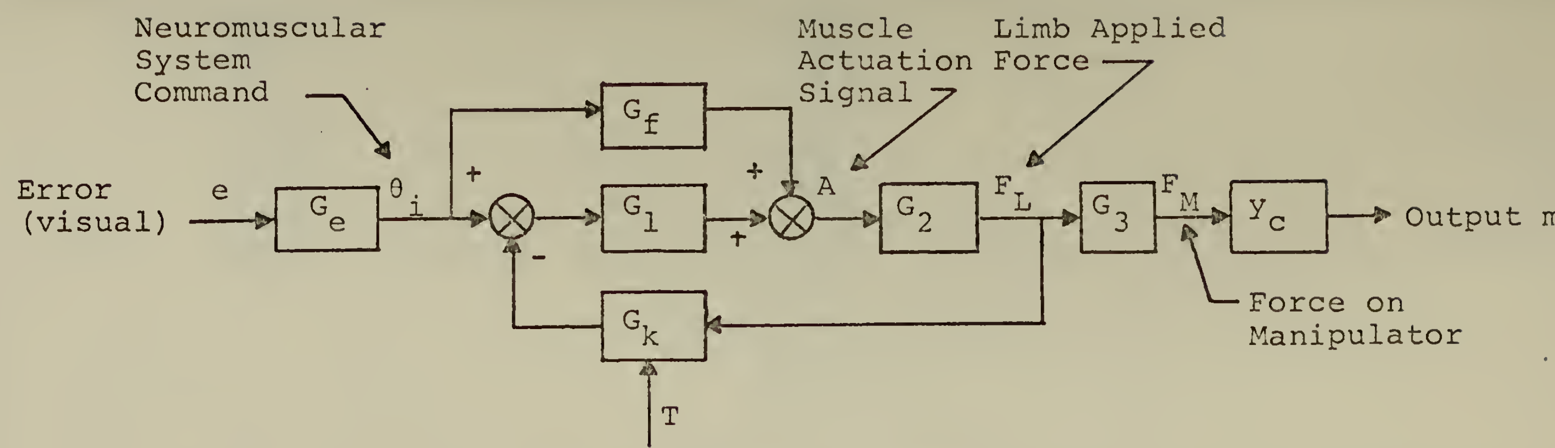
Subject Data

Subject	Age	Height	Weight	Flying Hours	λ_c	P_m psi
JT	31	71	168	1800 prop	5.65	20.08
LK	27	73	195	1450 jet	5.13	16.47
RK	28	71	155	1116 prop	5.44	10.66
JA	27	70	175	1500 prop	5.01	11.73

TABLE II

Forcing Function Components

	Freq. rad/sec	Amp. in.	Freq. rad/sec	Amp. in.	Freq. rad/sec	Amp. in.	Freq. rad/sec	Amp. in.
i_H	.502	.367	1.256	.342	3.01	.152	6.282	.0403
i_V	.502	.367	1,256	-.342	3.01	.152	6.282	-.0403



G_e = central computational delays, equalization and gain adjustment, synaptic and conduction delays to centers involved etc.

G_1, G_2 = actuation elements

G_f = command feed forward

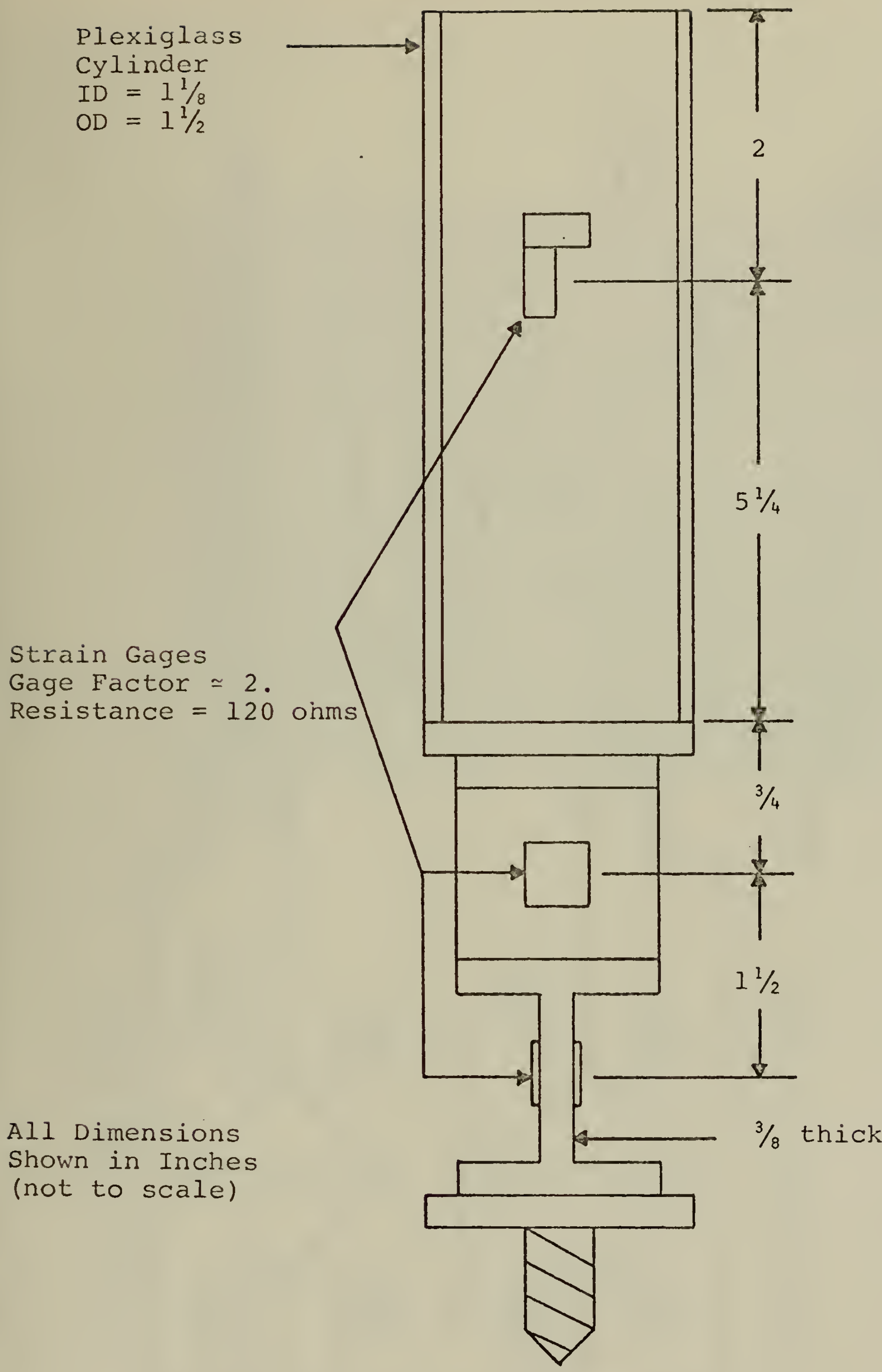
G_3 = force input-output characteristics of limb

G_k = force feedback elements

y_c = controlled element

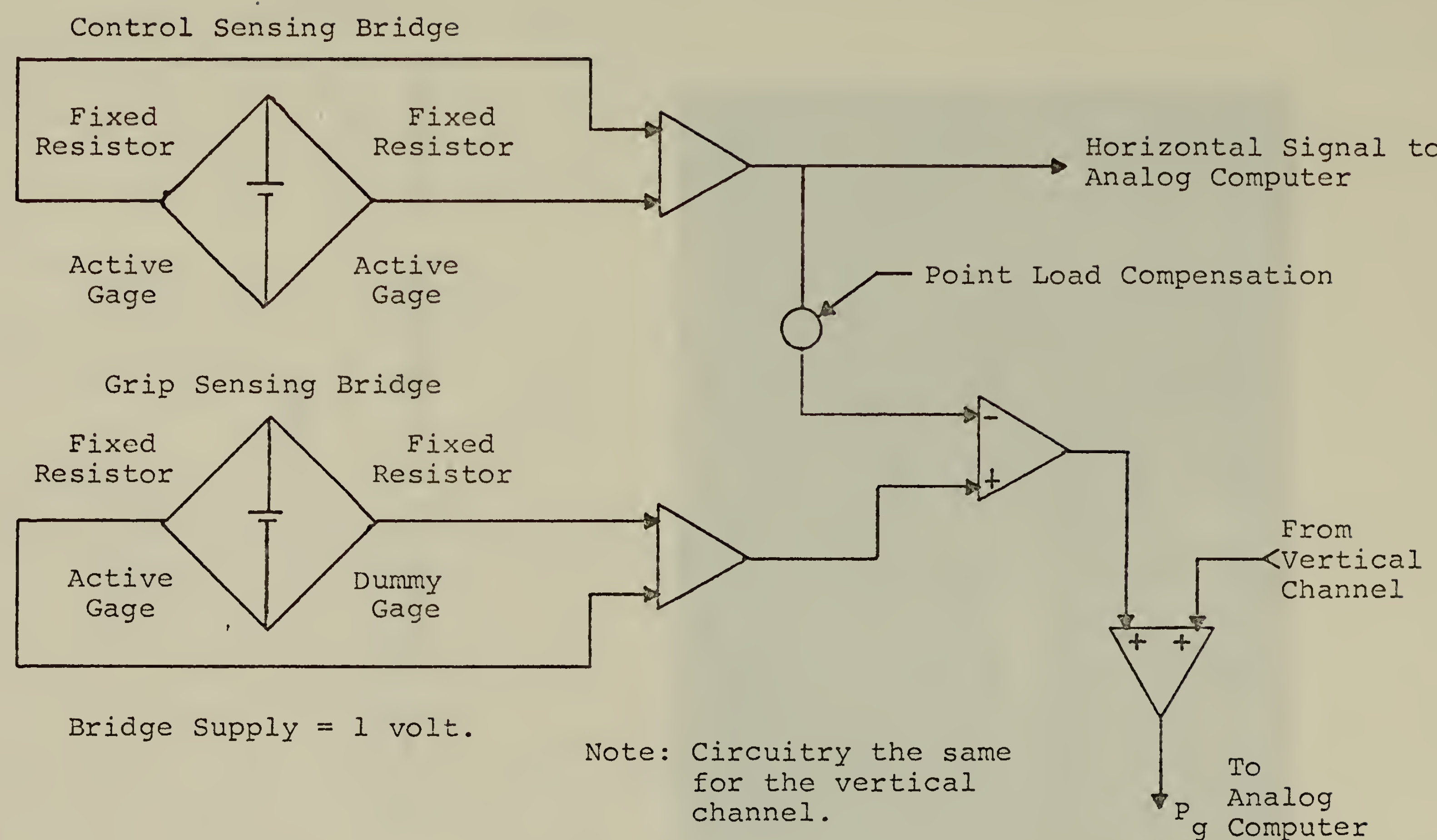
Open Loop Neuromuscular System for Force Control

Figure 1



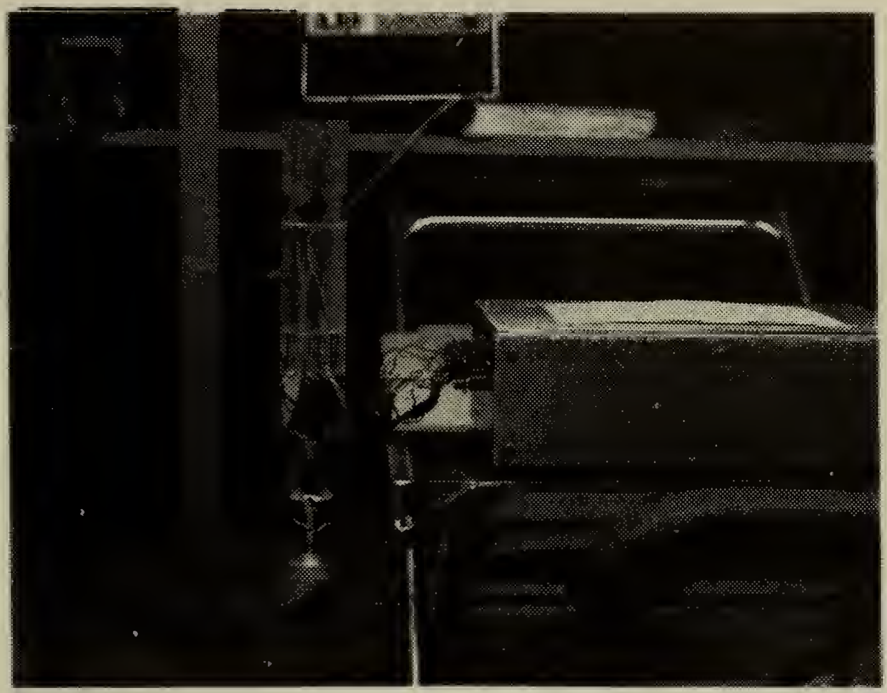
Prototype Isometric Controller

Figure 2



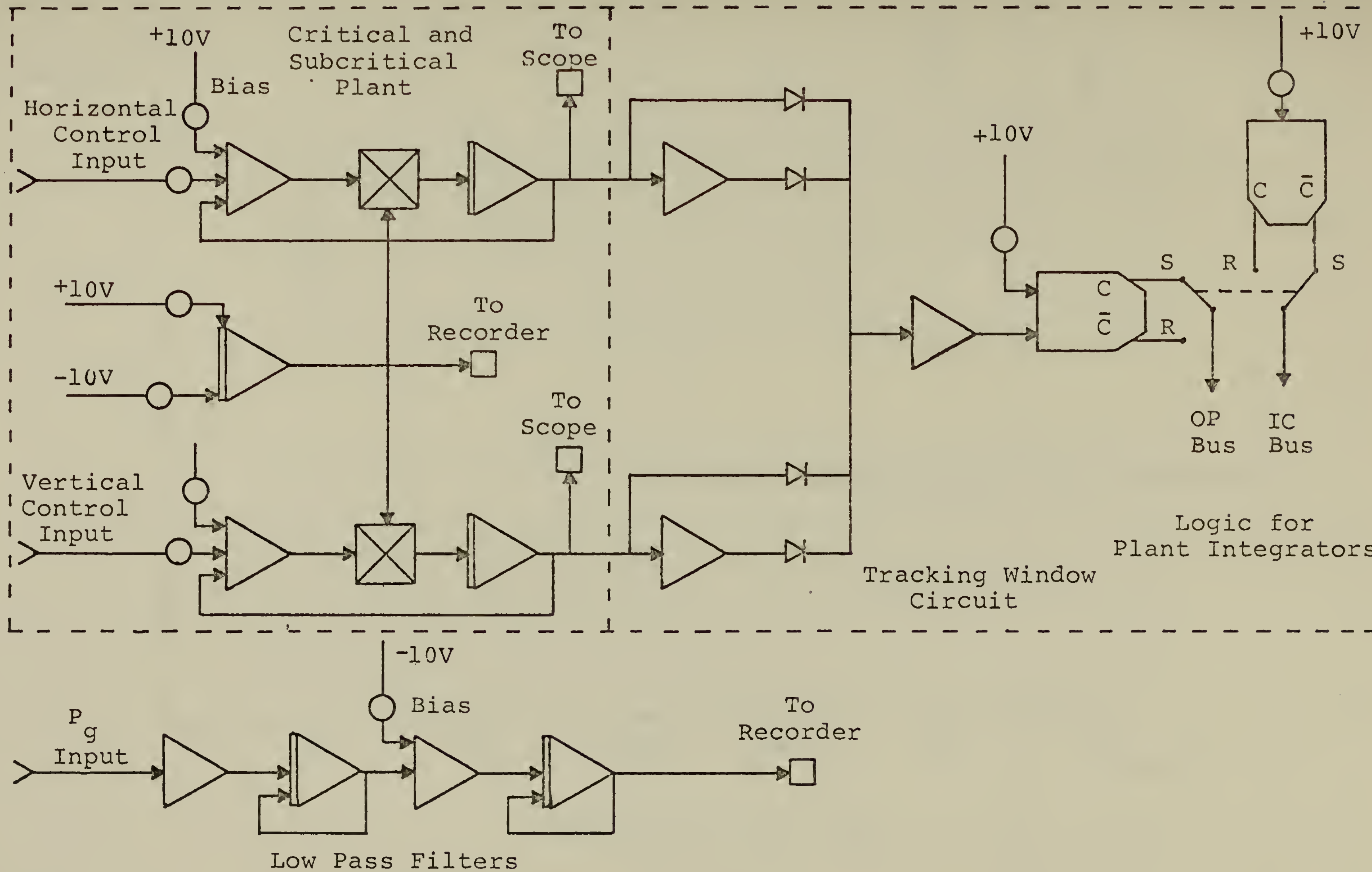
Controller Instrumentation

Figure 3



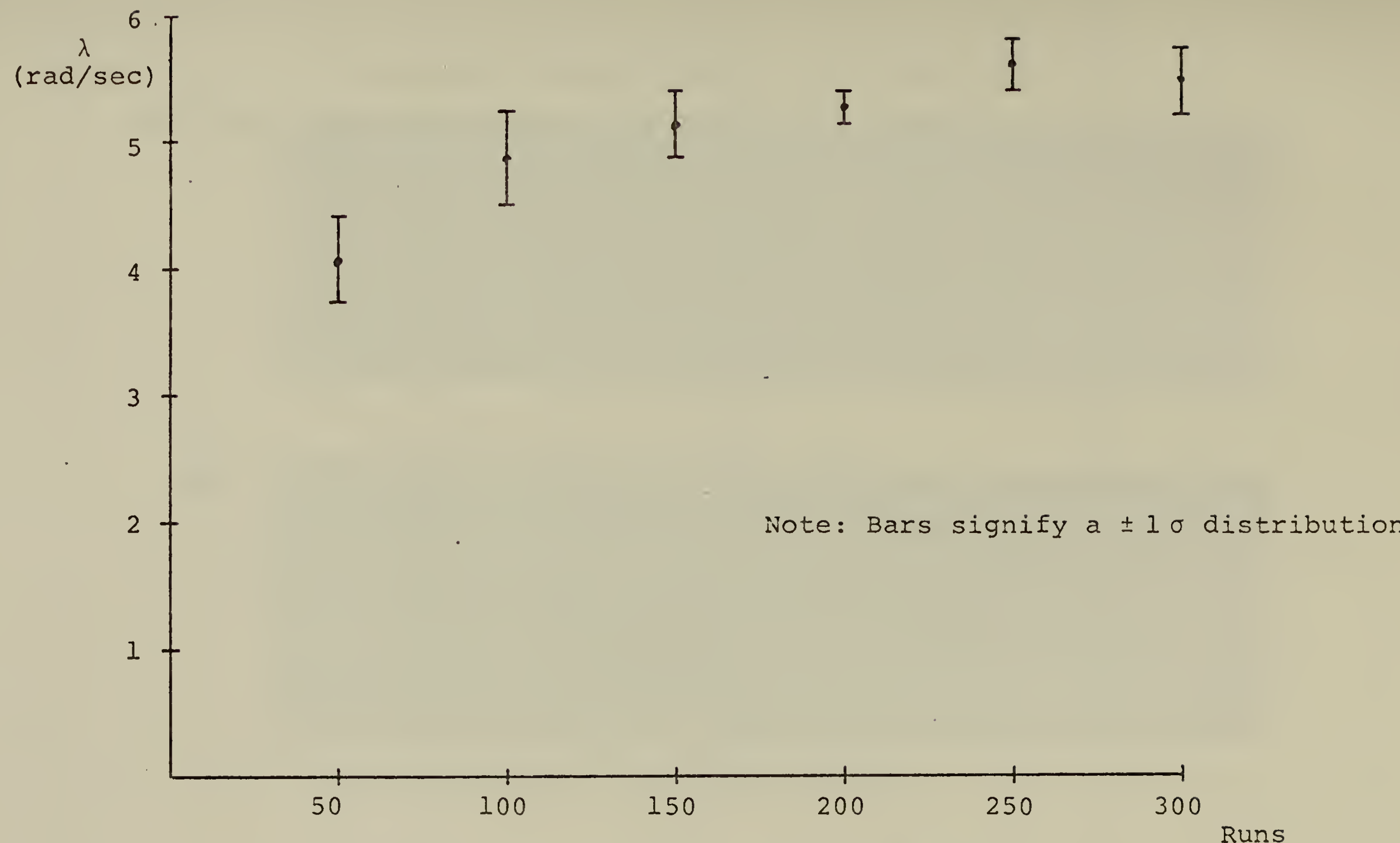
Isometric Controller and Instrumentation Box

Figure 4



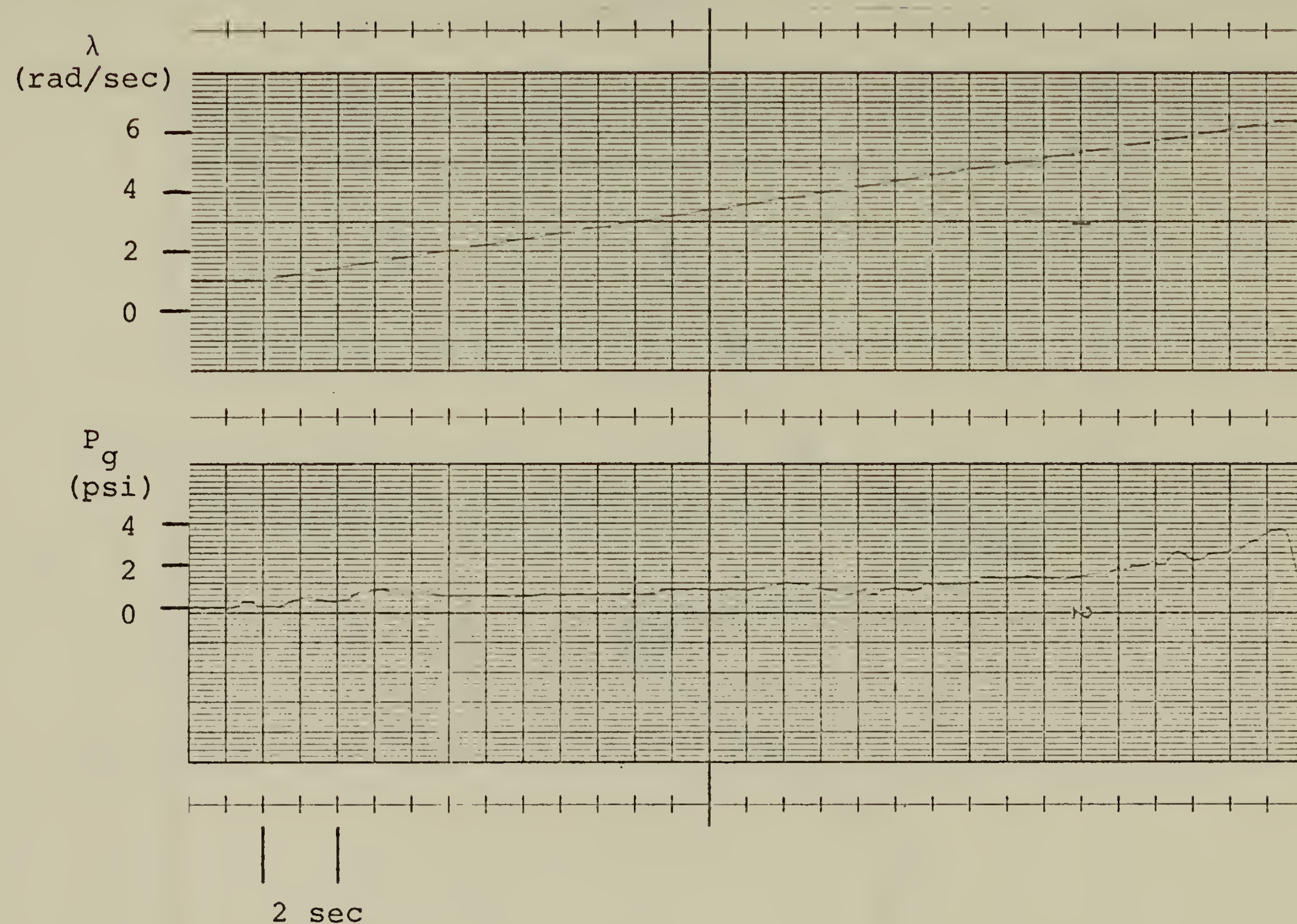
Analog Computer Diagram for Critical and Subcritical Tasks

Figure 5



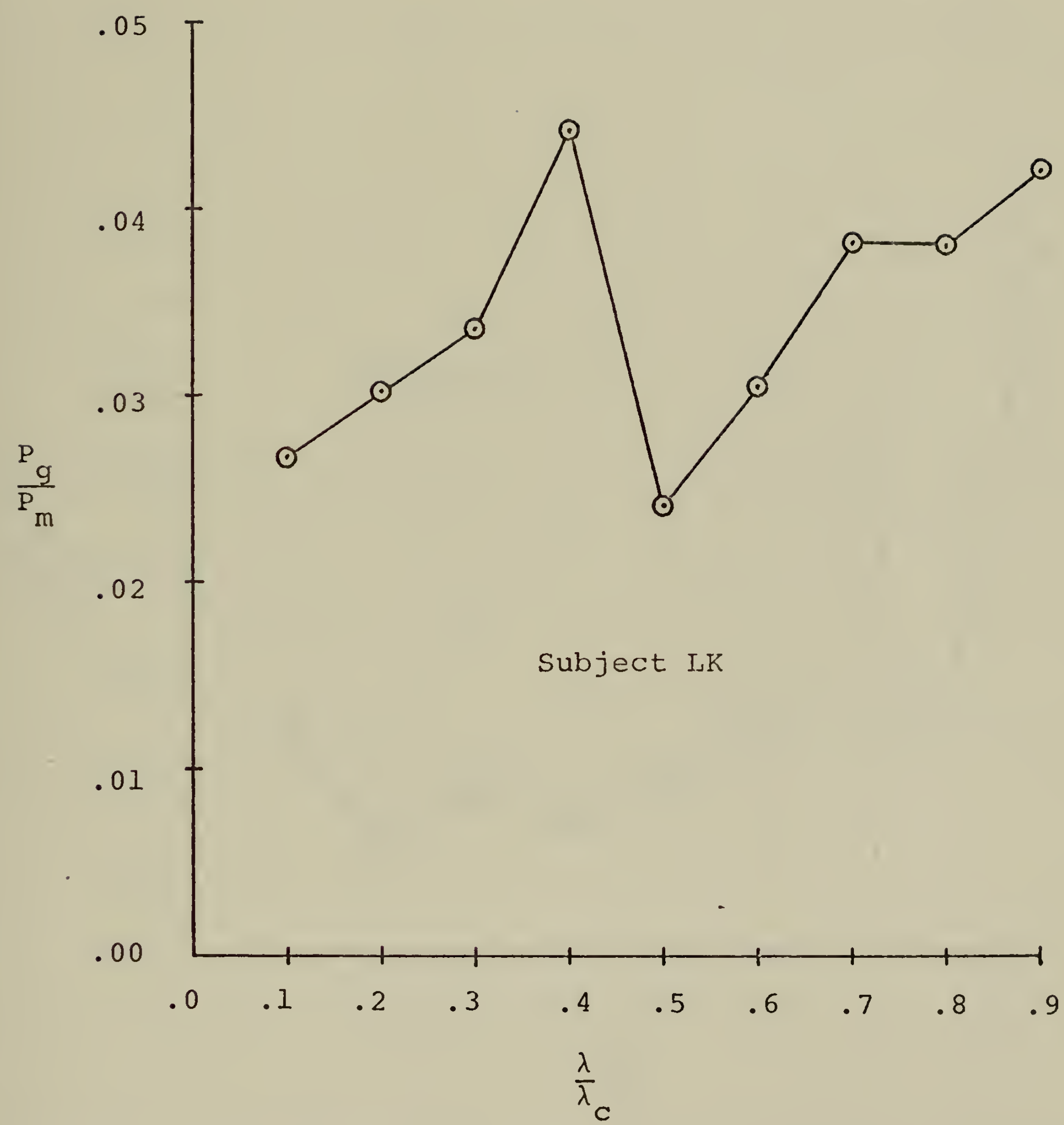
Typical Learning Curve

Figure 6



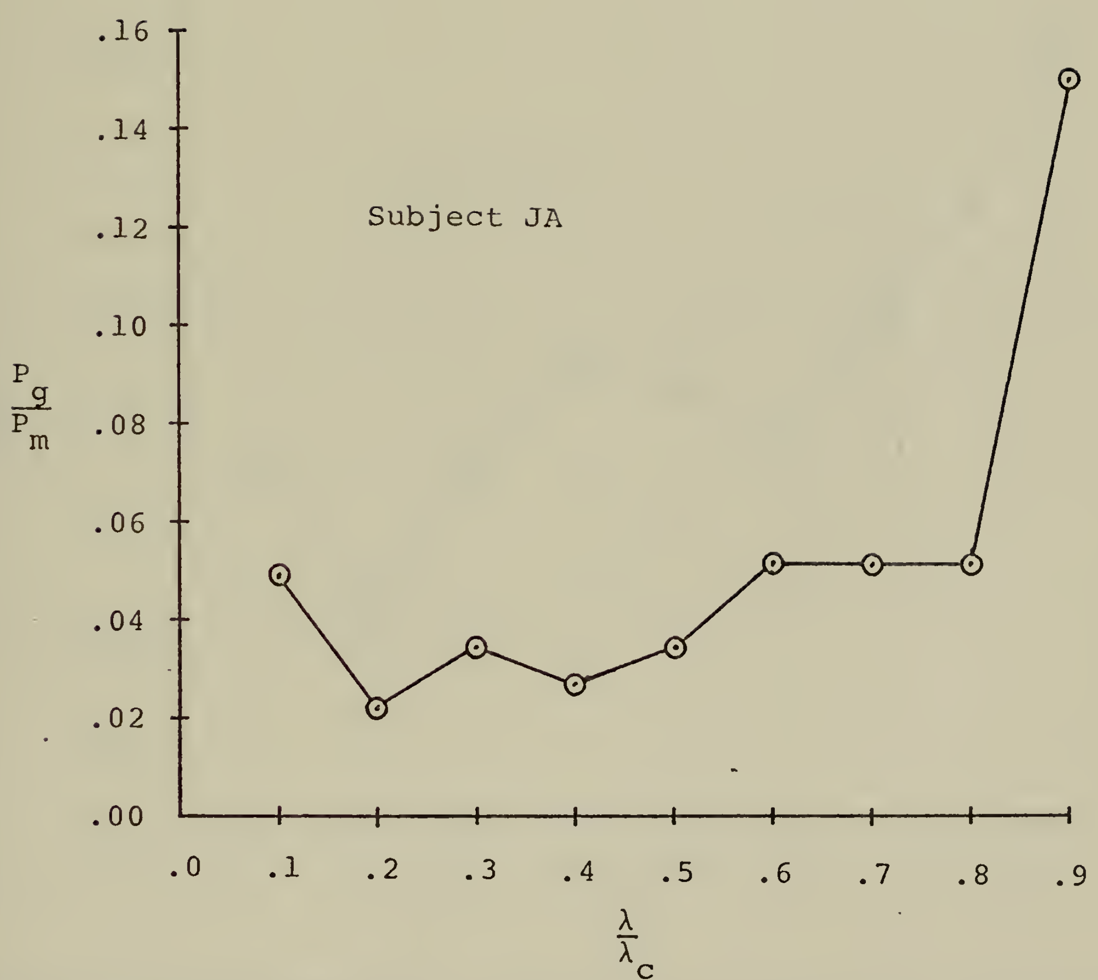
Typical Recording of λ and P_g During Critical Task Tracking

Figure 7



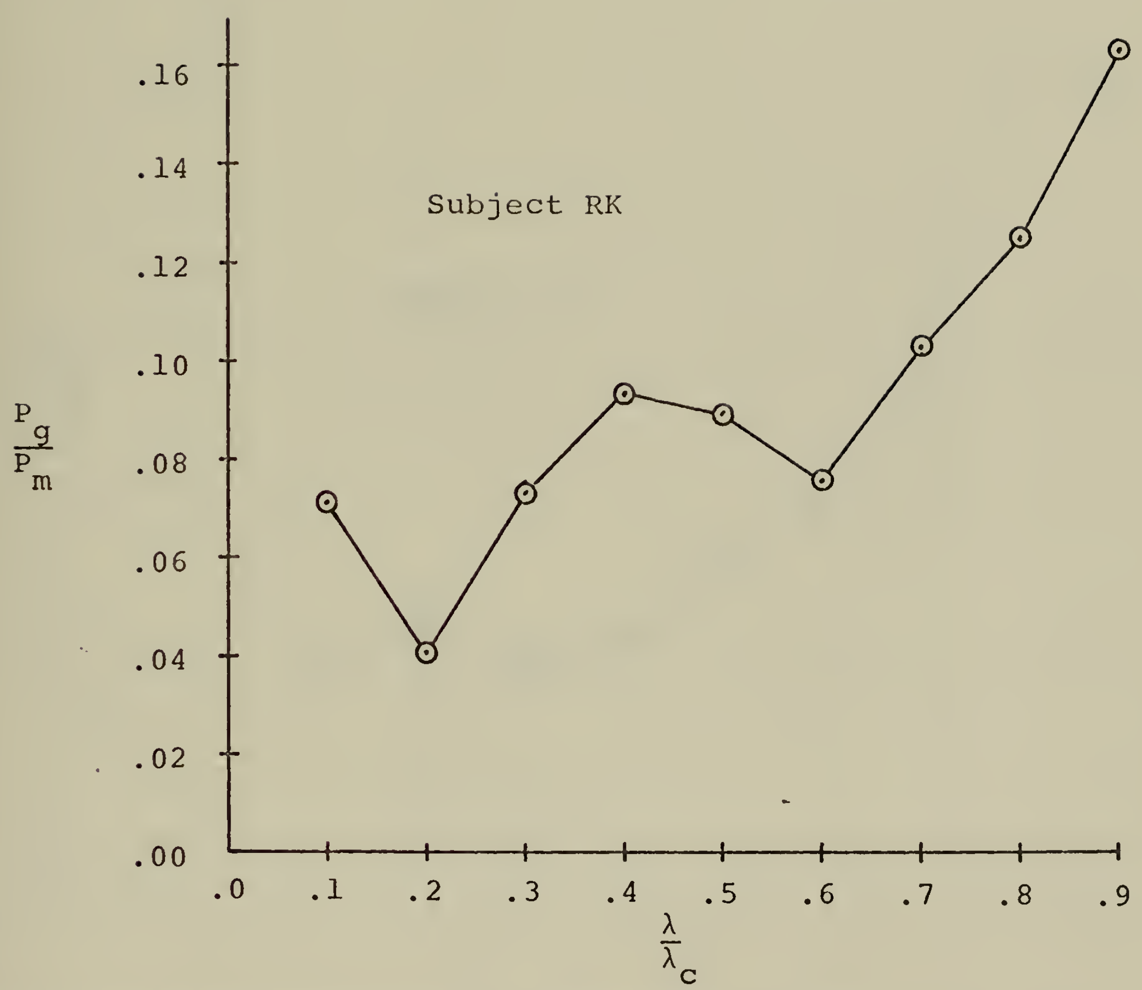
Normalized Grip Pressure vs. Proportion of Workload Capacity

Figure 8



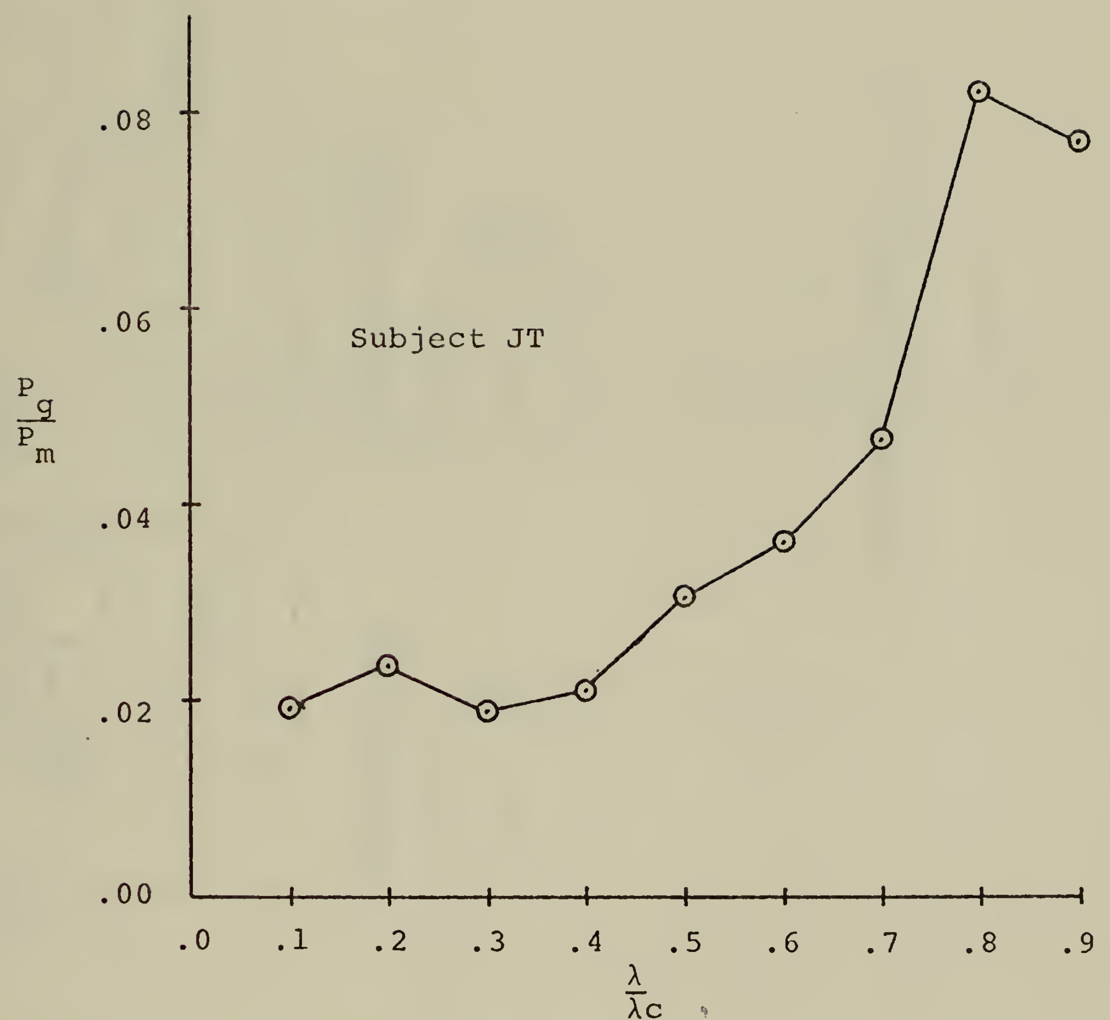
Normalized Grip Pressure vs. Proportion of Workload Capacity

Figure 9



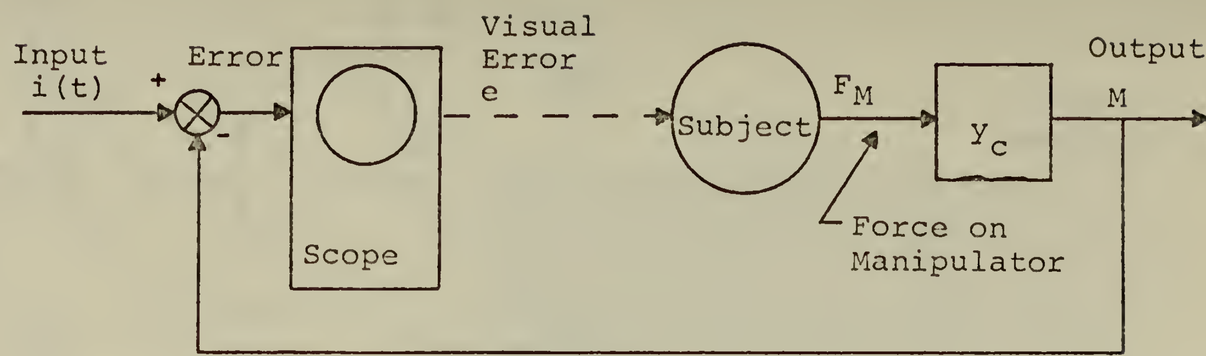
Normalized Grip Pressure vs. Proportion of Workload Capacity

Figure 10



Normalized Grip Pressure vs. Proportion of Workload Capacity

Figure 11



Critical Task

$i(t) = 0$

$y_c(S) = \frac{\lambda}{S-\lambda}$

$\lambda = 1 + .2t$

Subcritical Task

$i(t) = 0$

$y_c(s) = \frac{\lambda_S}{S-\lambda_S}$

$0 < \lambda_S < \lambda_c$

$\frac{K}{S}$ Task

$i(t) = \Sigma A_K \sin \Omega_K t$

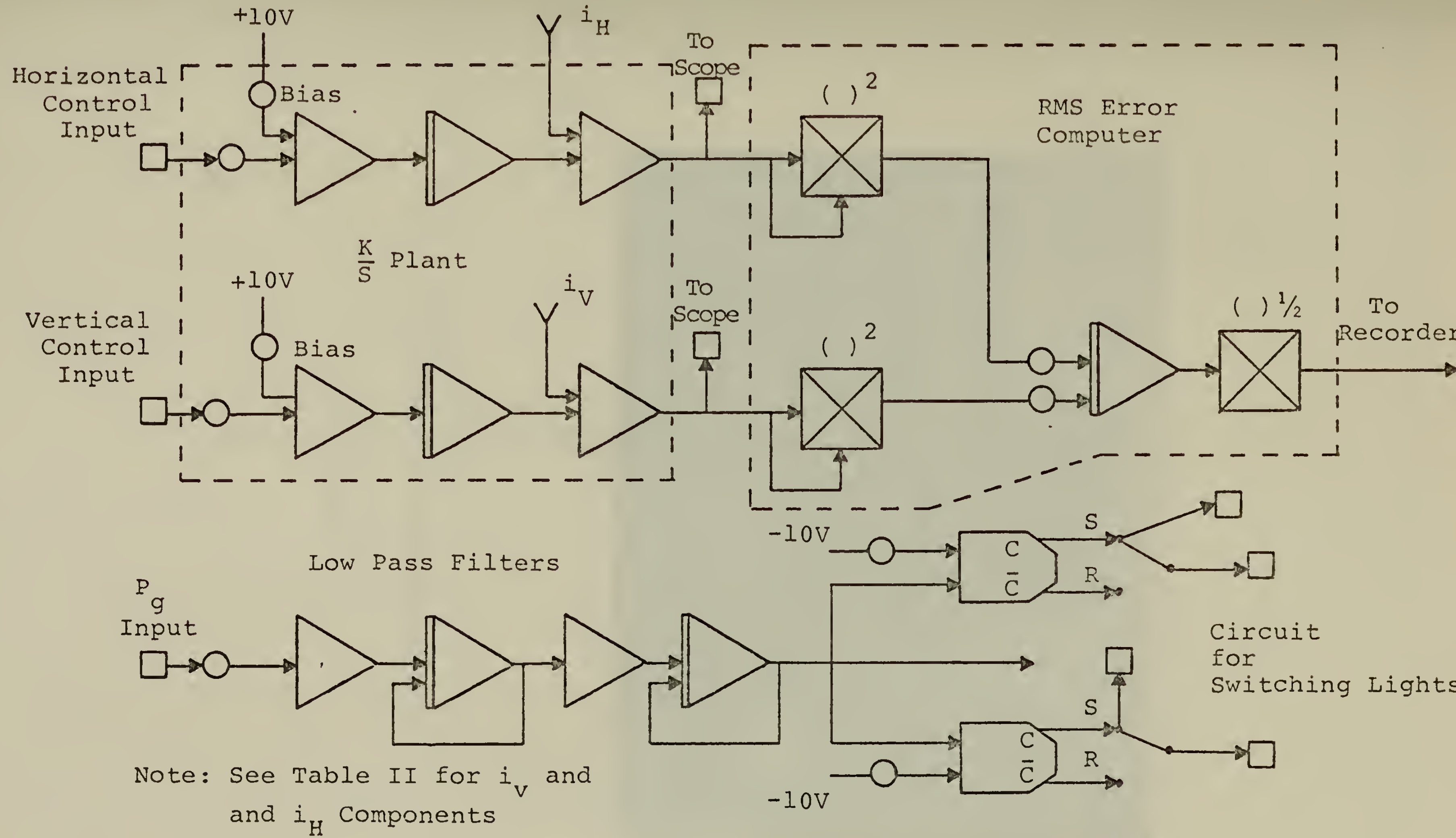
= random appearing sum of sinusoids

$y_c(S) = \frac{K}{S}$

$i(t)_{RMS} = .372$ in.

Compensatory Tracking Task

Figure 12

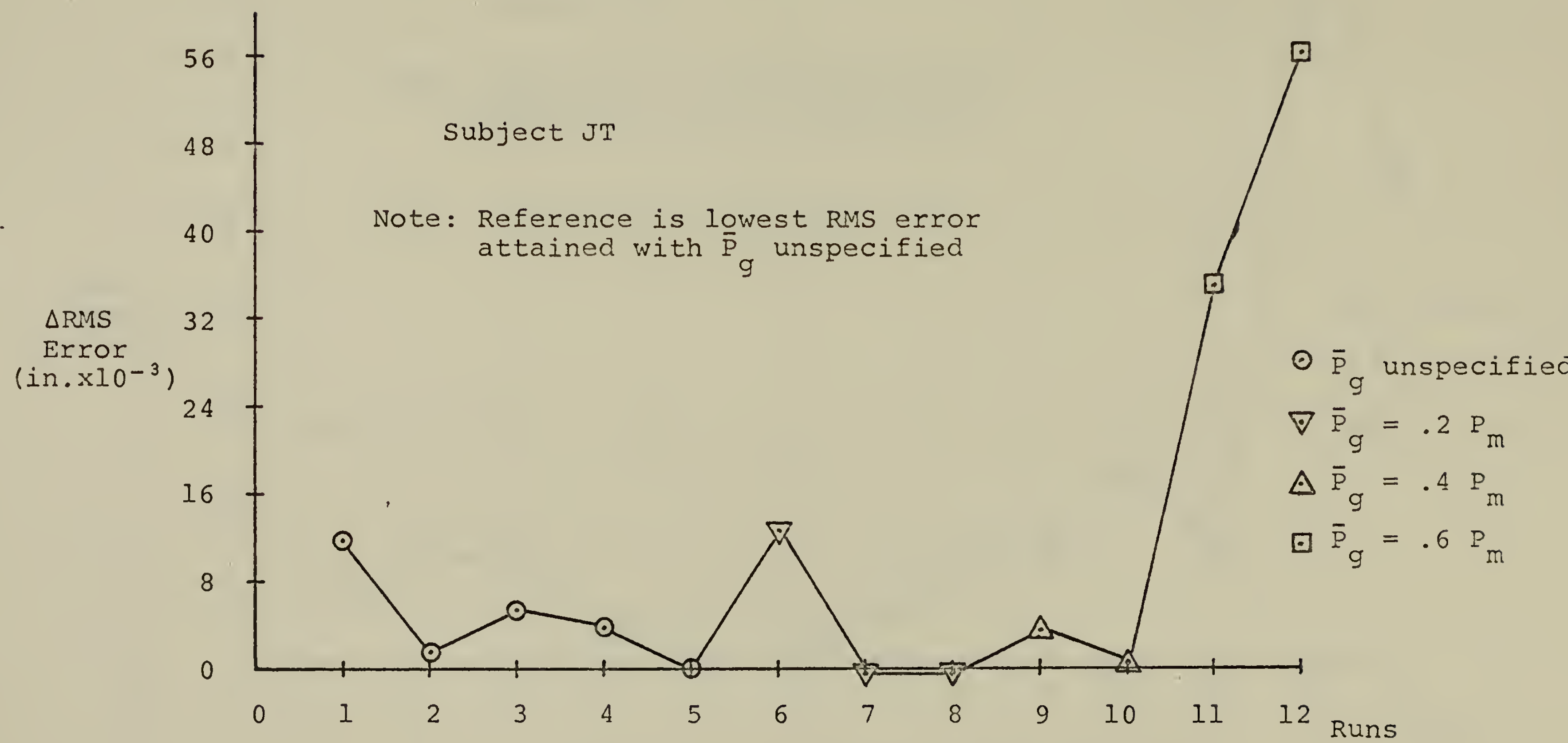


Analog Circuit for Tracking Performance Measurement

Figure 13

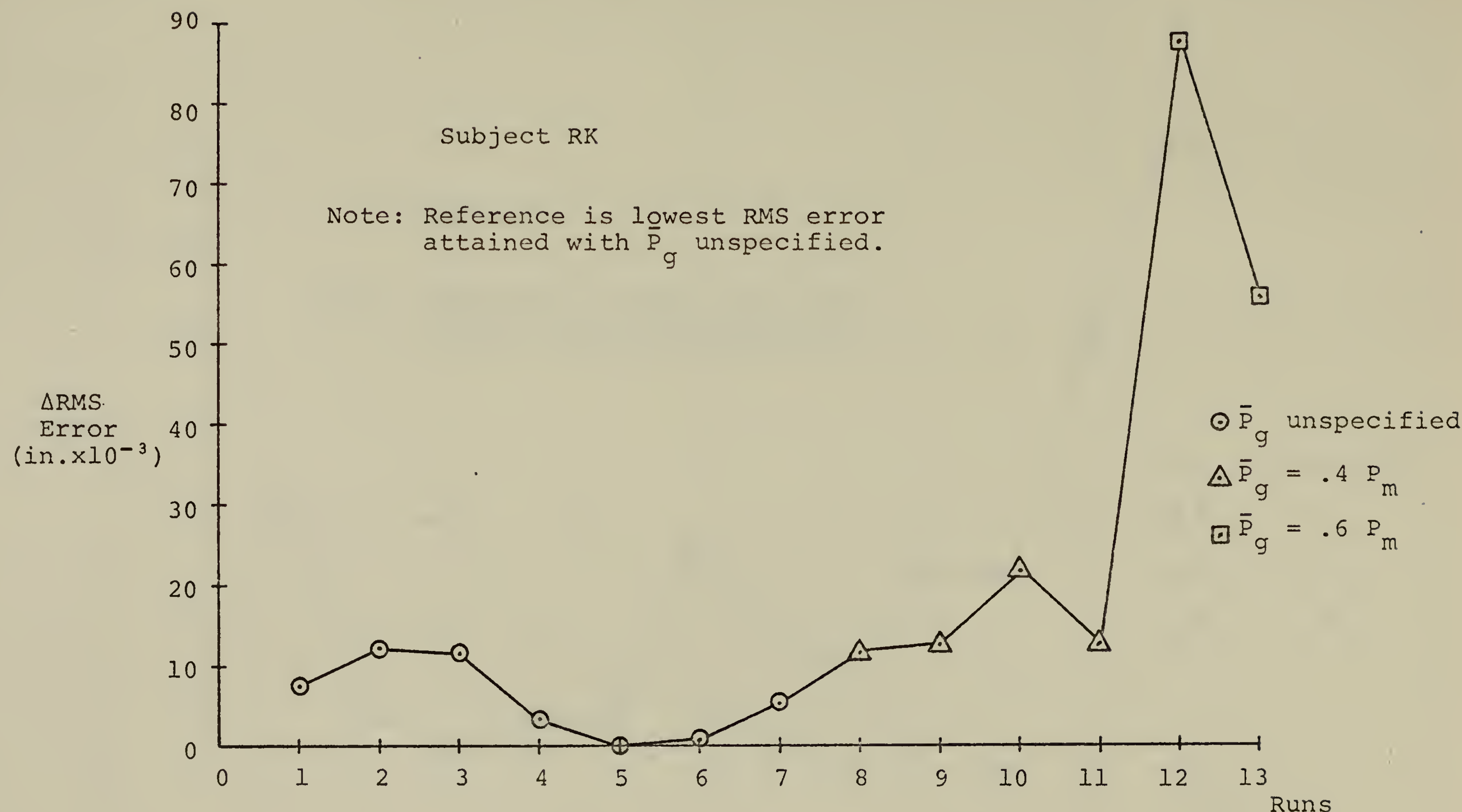
Secondary Task Configuration

Figure 14



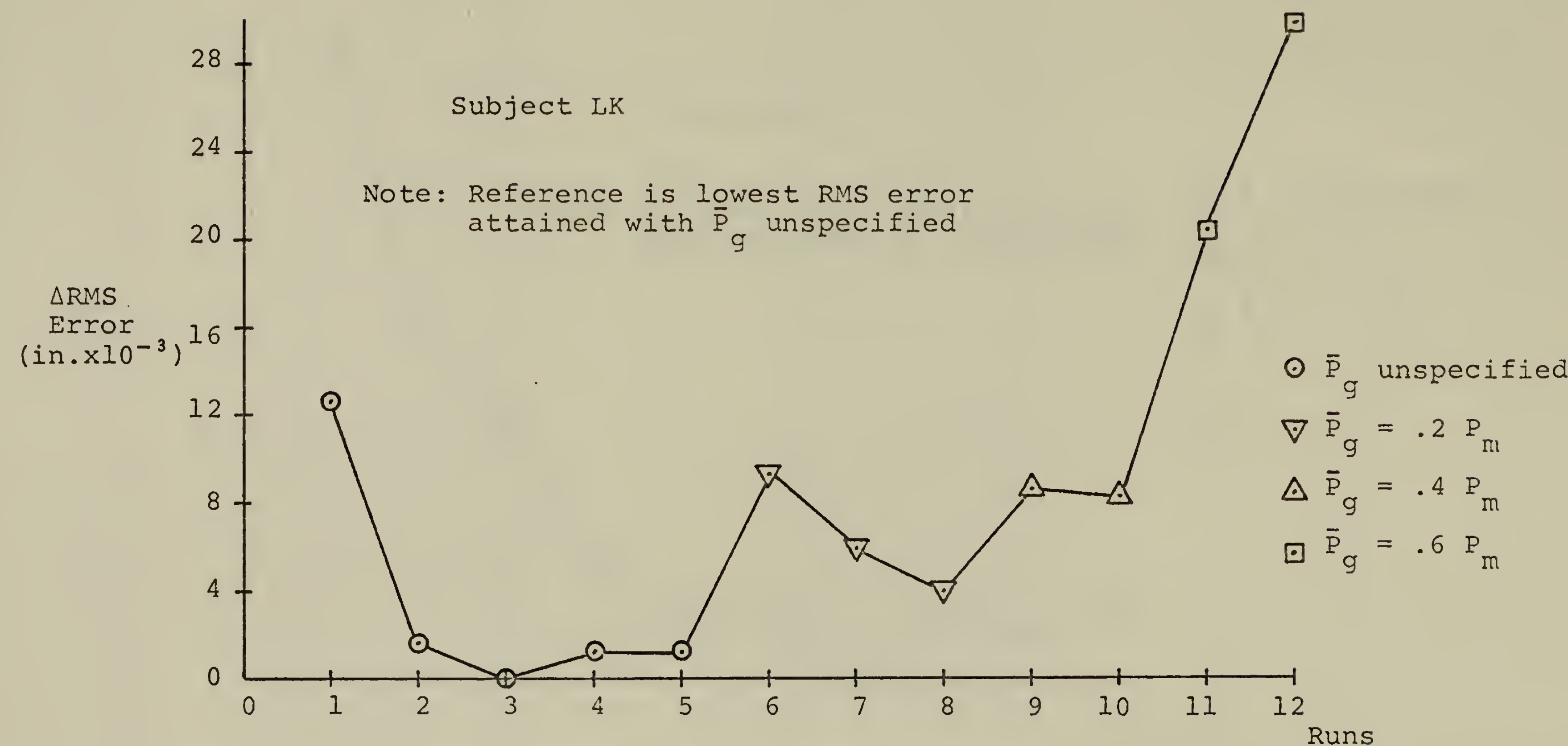
ΔRMS Error vs. Average Grip Pressure

Figure 15



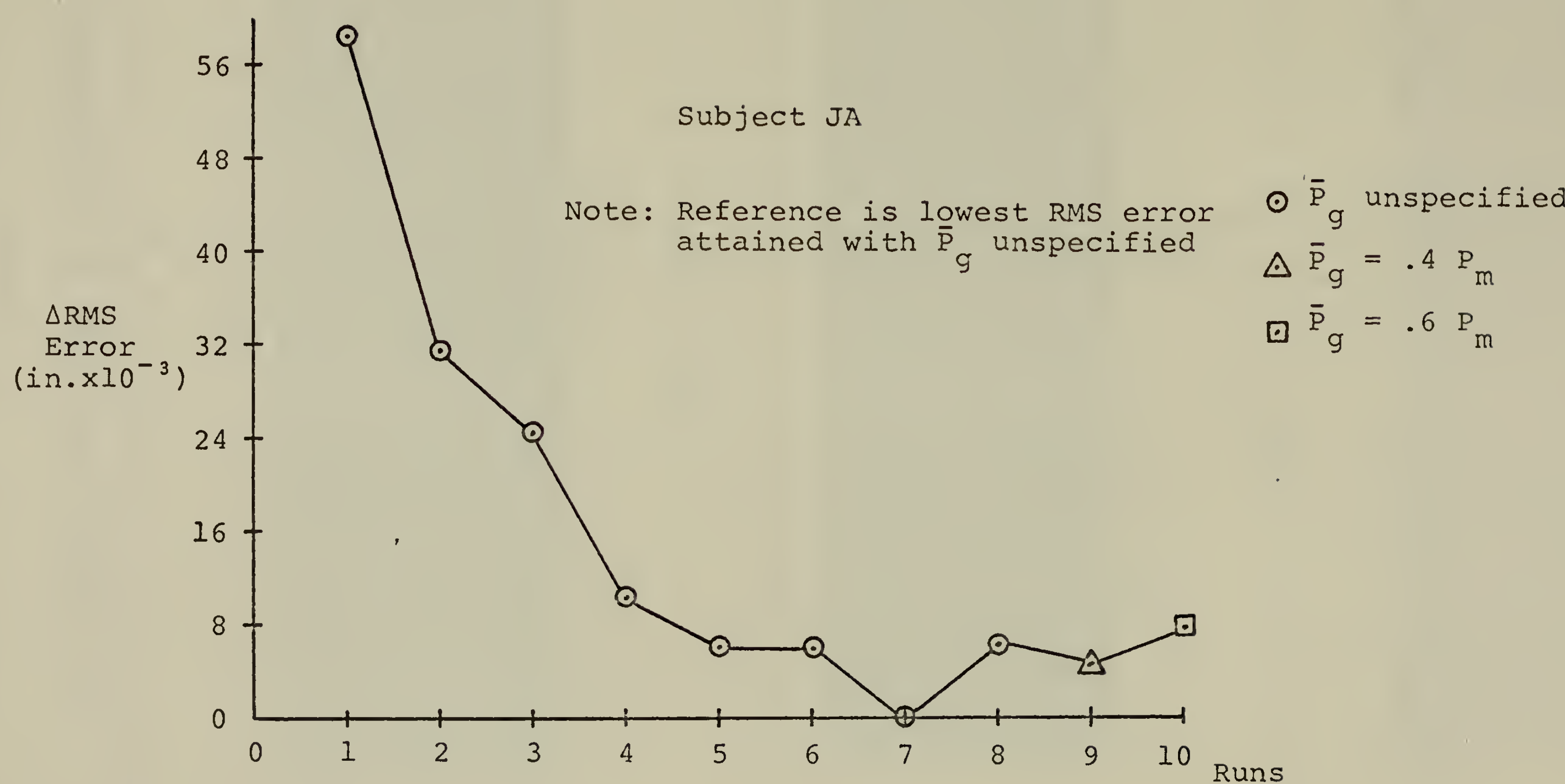
ΔRMS Error vs. Average Grip Pressure

Figure 16



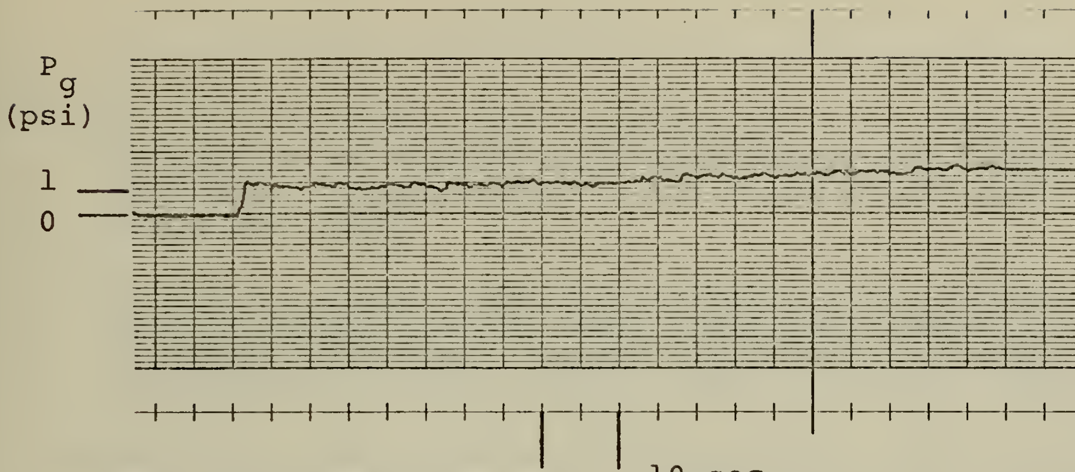
ΔRMS Error vs. Average Grip Pressure

Figure 17

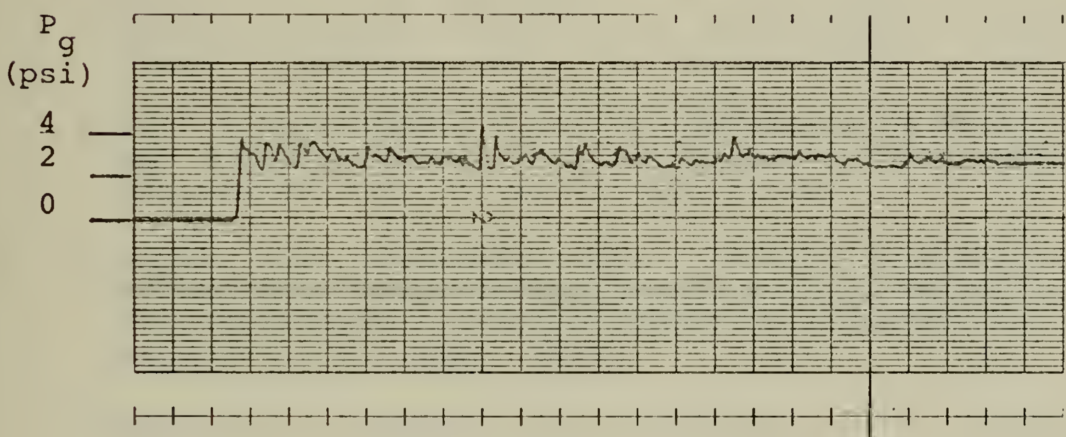


ΔRMS Error vs. Average Grip Pressure

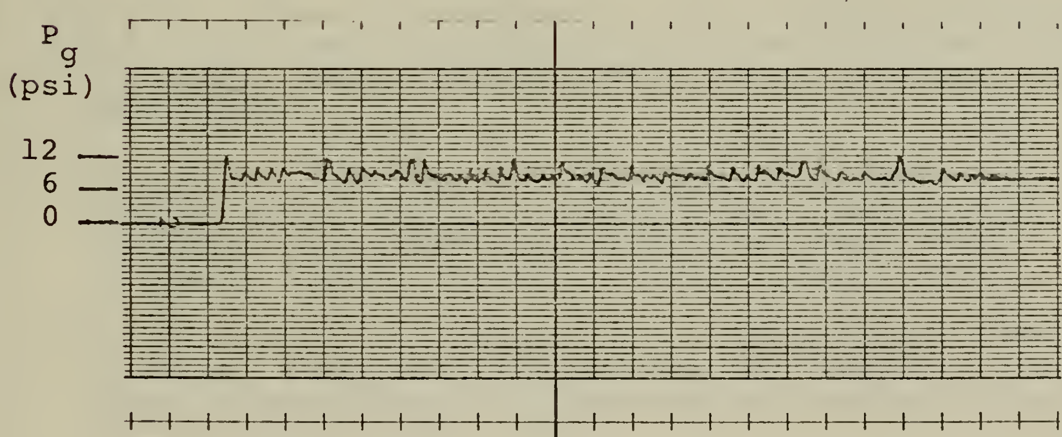
Figure 18



$\bar{P}_g = .2\ P_m$



$\bar{P}_g = .4\ P_m$



$\bar{P}_g = .6\ P_m$

P_g Recorded for $\bar{P}_g$ Specified (Subject LK)

Figure 19

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ABSTRACT

The effects of operator workload on average grip pressure and of euromuscular tension on tracking performance were the objects of this esearch. In one experiment, a "sub-critical" tracking task was performed by the operator while measurements of grip pressure were taken. n a second experiment, the operator was required to maintain average rip pressure at specified levels during 100-second tracking tasks hile his RMS tracking error was measured. The results clearly inicate that average grip pressure increases as the workload increases nd that higher average grip pressures result in higher RMS tracking rror values.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Controller						
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Neuromuscular Tension						

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